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Annex D — Trajectory Identification and A-to-B Transfer Characterization for QHD

Scope

This Annex D extension defines a methodological expansion of the Quantum Hash Descriptor (QHD) framework so that it can identify, track, and validate the trajectory of an object between a declared initial state A and a declared final state B , rather than describing only a single snapshot state at one epoch. The original QHD Phase A formulation established a deterministic identity, serialization, and cryptographic representation for a time-indexed astronomical state, including metadata, entropy normalization, energetic scale, and canonical hashing [file:134][file:133].

The present phase is designed to introduce a trajectory-layer representation that supports path identification, temporal chaining, transfer reconstruction, and provenance-grade validation of motion across two or more states [file:132][file:134].

Conceptual objective

Phase A answers the question: “What is the deterministic identity of object O at time t under a declared protocol?” [file:134][file:133] Annex D answers a different question: “What is the deterministic identity of the transfer or trajectory segment that carries object O from state A to state B under a declared dynamical and observational policy?” [file:132]

This distinction is essential. A single-state descriptor is not sufficient to characterize motion history, transfer structure, or inferred path geometry. The methodological annex for the second-generation N-body proof of concept already established that trajectory validation requires a dedicated dynamical layer in addition to the QHD identity layer [file:132]. Annex D therefore formalizes that missing layer at the protocol level.

Annex D object of description

In Annex D, the primary entity is no longer only the instantaneous object-state $\Xi_O(t)$, but a directed trajectory segment between two declared endpoints. The fundamental Annex D object can be denoted as:

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$$\Theta_O(A \rightarrow B) = (\Xi_O(t_A), \Xi_O(t_B), \mathcal{D}_{A \rightarrow B}, \Pi_{A \rightarrow B}, \mathcal{M}_{A \rightarrow B})$$

where:

- $\Xi_O(t_A)$ is the canonical Phase A state at the initial epoch.
- $\Xi_O(t_B)$ is the canonical Phase A state at the final epoch.
- $\mathcal{D}_{A \rightarrow B}$ is the declared dynamical model used to connect the endpoints.
- $\Pi_{A \rightarrow B}$ is the path representation or trajectory summary.
- $\mathcal{M}_{A \rightarrow B}$ is the transfer metadata layer.

This construction preserves compatibility with Phase A while adding the minimum structural components necessary for trajectory identity [file:134][file:132].

Endpoints A and B

The endpoints must be explicitly declared. In Annex D, point A is not merely a spatial coordinate, and point B is not merely another coordinate. Each endpoint is a complete state specification with at least the following fields:

- Object identifier.
- Epoch.
- Reference frame.
- Position vector.
- Velocity vector, if available.
- Uncertainty or confidence descriptor.
- Source of observation or simulation.
- Protocol version.

This requirement follows directly from the methodological logic already introduced in the validation annexes, where reproducibility depends on declared time scale, frame, and data source rather than on geometry alone [file:132][file:131][file:133].

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Trajectory descriptor

A Annex D trajectory must include an intermediate transfer representation that is distinct from the endpoint states. A practical formulation is:

$$\Pi_{A \rightarrow B} = (\Delta t, \Delta \vec{r}, \Delta \vec{v}, L, \bar{v}, \kappa, \mathcal{S}, \mathcal{U})$$

where:

- $\Delta t = t_B - t_A$ is the elapsed propagation time.
- $\Delta \vec{r} = \vec{r}_B - \vec{r}_A$ is the net displacement.
- $\Delta \vec{v} = \vec{v}_B - \vec{v}_A$ is the net velocity change when defined.
- L is the estimated path length.
- $\bar{v}$ is the average transport speed under the declared model.
- κ is a path-curvature or nonlinearity summary.
- $\mathcal{S}$ is a segmentation or sampling policy.
- $\mathcal{U}$ is an uncertainty model or confidence field.

This representation is deliberately compact. It does not attempt to store the full physical history in one scalar, but it provides enough structure to distinguish a straight transfer, an orbital arc, a ballistic expansion, or a strongly perturbed path.

Transfer hash

The Annex D discrete identifier should not reuse the Phase A single-snapshot hash unchanged. Instead, it should hash a canonical transfer tuple. A suitable form is:

$$h_{q,B}(O; A \rightarrow B) = \text{SHA3-256}(\text{Serialize}(\Theta_O(A \rightarrow B)))$$

A minimal canonical tuple may be defined as:

$$\Theta_O(A \rightarrow B) = (h_q(O; t_A), h_q(O; t_B), \Pi_{A \rightarrow B}, \mathcal{D}_{A \rightarrow B}, \mathcal{M}_{A \rightarrow B})$$

This preserves backward compatibility with Phase A because each endpoint remains represented by the already declared QHD state hash [file:131][file:133][file:134].

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Dynamical model layer

The methodological annex for the second-generation N-body proof of concept established that high-fidelity trajectory validation requires a declared dynamical propagation layer rather than relying on identity logic alone [file:132]. Annex D therefore requires every trajectory descriptor to carry a declared dynamical policy, even if the path is partly inferred or reconstructed.

At minimum, the dynamical layer should specify:

- Propagation class: ballistic, Keplerian, N-body, relativistic, hydrodynamic, or hybrid.
- Force model.
- Reference frame.
- Time scale.
- Numerical integration policy.
- Sampling cadence.
- External ephemeris or observational anchors.
- Confidence or uncertainty assumptions.

Without this layer, the same endpoints could be connected by many physically incompatible paths, making the transfer identity scientifically ambiguous [file:132].

Regular and irregular trajectories

The second-generation methodological annex already distinguished regular and irregular trajectory classes in the validation context [file:132]. Annex D extends that distinction operationally.

A **regular trajectory** is one for which the motion can be approximated within a declared class of stable or weakly perturbed dynamics, such as planetary transfer arcs, orbital segments, or predictable long-horizon propagation under a stable force model. An **irregular trajectory** is one for which the path may involve fragmentation, shock-driven expansion, stochastic perturbation, strong uncertainty growth, partial observability, or non-gravitational effects [file:132].

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This distinction matters because not every moving object can be treated under a simple planet-like trajectory model. In many cases, the identification problem becomes one of transfer inference under partial observational constraints, not merely deterministic celestial propagation.

Recommended Annex D metadata

For trajectory identification between A and B, the metadata layer should be expanded relative to Phase A. A recommended minimum structure is:

Field	Purpose
objectname	Tracked object or fragment label
objectclass	Planet, fragment, ejecta, debris, dust packet, etc.
trajectoryclass	Regular, irregular, ballistic, orbital, diffusive, reconstructed
sourceevent	Optional origin event identifier
epochA	Initial epoch
epochB	Final epoch
referenceframe	Spatial frame
timescale	TAI, TDB, UTC-derived, or declared astrophysical time policy
datasourceA	Initial-state source
datasourceB	Final-state source
dynamicmodel	Declared propagation model
uncertaintyclass	Confidence or reconstruction category
serializationversion	Annex D protocol version

This is consistent with the Phase A and annex logic that metadata is not ornamental but constitutive of reproducibility and identity [file:134][file:131][file:132][file:133].

Sampling policy

A trajectory between A and B should never be reduced to only two endpoint states when the path itself matters. Annex D should therefore declare a sampling policy:

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$$\mathcal{S}_{A \rightarrow B} = \{t_0, t_1, \dots, t_n\}$$

with associated intermediate states:

$$\Xi_O(t_0), \Xi_O(t_1), \dots, \Xi_O(t_n)$$

The final transfer hash may then be built either from a compact path summary or from a chained sequence of sampled states. For high-rigor applications, the preferred form is a state chain:

$$h_{q,B}^{chain} = \text{SHA3-256}(\text{Serialize}(h_q(t_0), h_q(t_1), \dots, h_q(t_n), \mathcal{M}))$$

This preserves compatibility with the Phase A concept of multi-snapshot chains already introduced in the original manuscript [file:134].

Validation logic for Annex D

Annex D must be validated at two different levels.

Level 1: Endpoint consistency

This level verifies that the states at A and B are individually well defined under the Phase A logic, including canonical serialization, explicit metadata, and deterministic digest generation [file:131][file:133].

Level 2: Transfer consistency

This level verifies that the inferred or propagated path from A to B is reproducible under the declared trajectory model. At minimum, validation should test:

- Same endpoints plus same model produce the same transfer descriptor.
- Same serialized transfer tuple produces the same Annex D digest.
- Different path assumptions between the same endpoints produce distinguishable transfer identifiers.
- Different sampling policies are versioned rather than silently mixed.
- Uncertainty propagation is explicitly represented for irregular cases.

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These requirements follow naturally from the logic used in Annex B, where deterministic identity depends on exact serialization and explicit policy declaration [file:131].

Annex D pseudocode concept

A minimal implementation-oriented pseudocode is:

INPUTS:

X_{iA} = canonical Phase A state at t_A

X_{iB} = canonical Phase A state at t_B

`dynamic_model`

`sampling_policy`

`uncertainty_policy`

`metadata_transfer`

STEP 1: Validate X_{iA} and X_{iB} under Phase A conformance rules.

STEP 2: Compute or reconstruct intermediate path states under `dynamic_model`.

STEP 3: Derive trajectory summary $\Pi_{\{A \rightarrow B\}}$.

STEP 4: Build canonical transfer object $\Theta_{\{A \rightarrow B\}}$.

STEP 5: Serialize $\Theta_{\{A \rightarrow B\}}$ in canonical JSON with sorted keys and fixed scalar policies.

STEP 6: Compute SHA3-256 over UTF-8 bytes.

STEP 7: Output transfer descriptor, canonical JSON, digest, and validation diagnostics.

This pseudocode should be interpreted as a protocol skeleton, not yet as a full physical solver.

Scientific limits

Annex D can support trajectory identification and transfer provenance before it supports perfect physical prediction. This is an important methodological distinction. A moving object may admit a meaningful transfer identity under declared assumptions even if the full physical history cannot yet be solved exactly.

Therefore, Annex D should initially claim the following narrower but rigorous capability:

- Deterministic identification of a declared transfer hypothesis from A to B.
- Reproducible hashing of trajectory segments under explicit dynamical and metadata assumptions.
- Compatibility with future high-fidelity propagation engines.

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- Support for both regular and irregular motion classes through declared model categories.

By contrast, Annex D should not initially claim exact reconstruction of all complex trajectories unless a fully validated physical solver is also supplied [file:132].

Recommended Annex D statement

A scientifically defensible manuscript statement would be:

“Annex D extends QHD from single-state deterministic identity to deterministic trajectory-segment identity, allowing an object or fragment to be described not only at an epoch but along a declared transfer from state A to state B. The resulting framework is suitable for provenance, trajectory comparison, and transfer-chain validation under explicitly declared dynamical assumptions, including regular orbital motion and irregular propagated motion.” [file:132][file:134]

Development path

A rigorous development path for Annex D should proceed in the following order:

1. Planetary two-endpoint transfers under stable orbital conditions.
2. Multi-snapshot orbital arcs with canonical chaining.
3. N-body transfer descriptors for planetary perturbation cases.
4. Fragmented or irregular trajectories with uncertainty fields.
5. Event-linked trajectories under declared propagation models.
6. Hybrid propagation plus observation-anchored reconstruction for partially observed objects.

This sequence is consistent with the methodological progression already established from Phase A through the N-body validation annex [file:133][file:132].

Annex status

This text may serve as the conceptual and methodological definition of Annex D for the QHD program. It is intended for direct inclusion in a scientific manuscript, methodological dossier, or proof-of-concept package as the formal extension from single-state identity toward deterministic trajectory identification and A-to-B transfer characterization [file:131][file:132][file:133][file:134].

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